STATE OF MICHIGAN
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RR2098
December 2011

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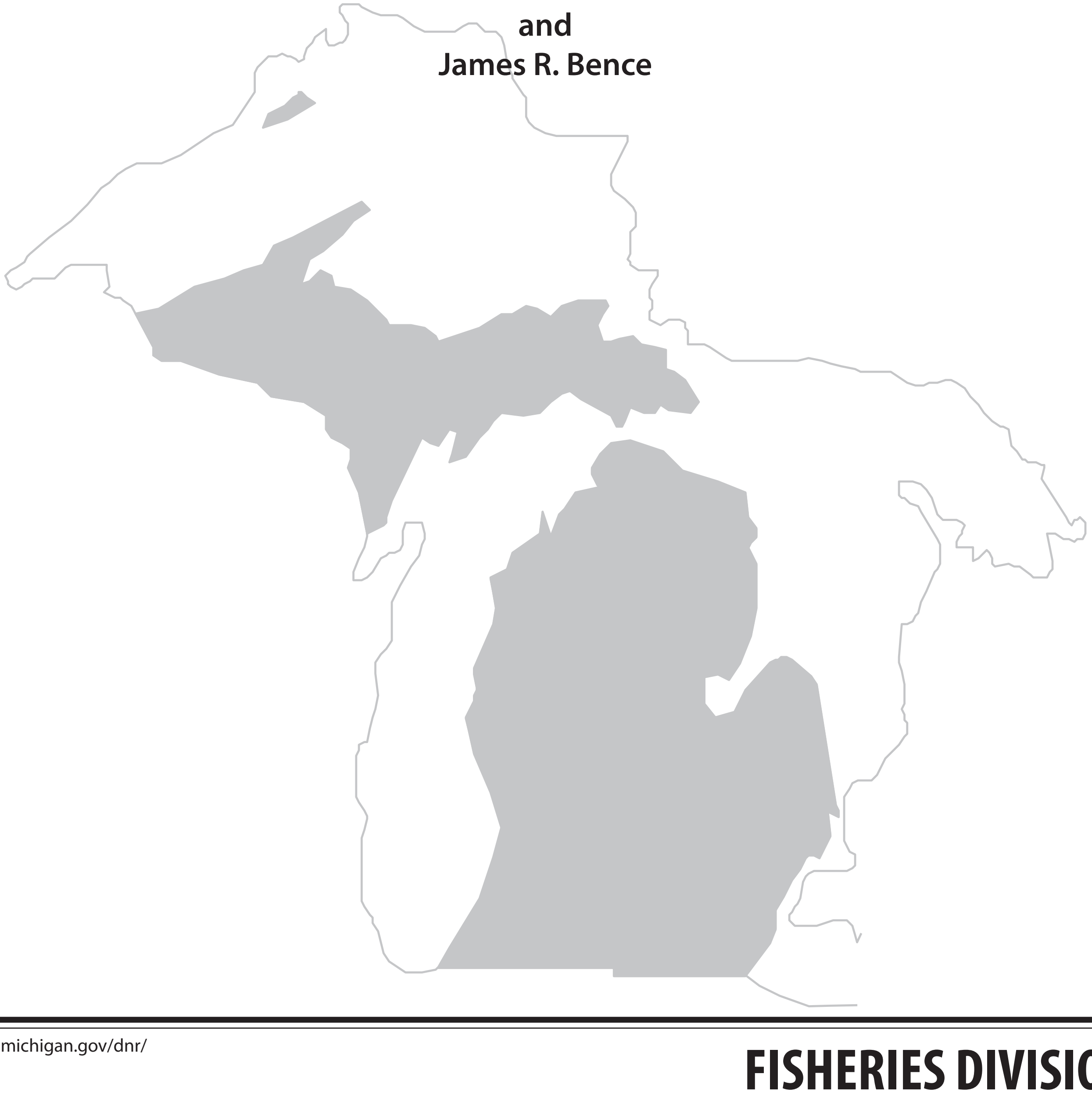

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FISHERIES DIVISION
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Suggested Citation Format

Linton, B. C., and J. R. Bence. 2011. Sensitivity analysis of stock assessment models for lake whitefish in the 1836 treaty waters of Lake Huron. Michigan Department of Natural Resources, Fisheries Research Report 2098, Lansing.

Michigan Department of Natural Resources
Fisheries Research Report 2098, 2011

Sensitivity Analysis of Stock Assessment Models for Lake Whitefish in the 1836 Treaty Waters of Lake Huron

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Abstract.–Recommendations for total allowable catch and harvest regulating guidelines for lake whitefish *Coregonus clupeaformis* stocks in the 1836 treaty waters of Lake Huron are determined using stock-specific statistical catch-at-age models, which were first developed during the negotiations of the 2000 Consent Decree. Due to the rapid development and implementation of the models, not all of the approaches used in them have been fully evaluated. Therefore, we performed a general analysis of the models' sensitivity to changes in "known" inputs and model structures. Our analysis revealed that one of the four stock assessment models evaluated was unstable since it converged to an alternate solution in nearly one-third of the changes tested. This alternate solution differed from the solution of the baseline (i.e., original) model, and provided a poorer fit to the observed data than did the baseline model. In addition, all of the stock assessment models were sensitive to changes in the methods used to estimate recruitment and gear selectivity, as well as to changes in their objective functions. Our results suggest that sensitivity analysis is useful for identifying both unstable models and sensitive model processes. Consequently, a sensitivity analysis should be conducted whenever the stock assessment models are updated.

Introduction

In 1836, Native American Bands in the region that was to become the state of Michigan signed a treaty with the U.S. government which reserved their right to fish in the Michigan waters of lakes Huron, Michigan, and Superior. These fishing rights were reaffirmed by the U.S. federal courts in 1979. The federal district court later approved fishery regulations created by the Chippewa/Ottawa Treaty Fishery Management Authority (COTFMA) in 1982, while mandating that total allowable catches (TACs) be established for important fish species to prevent over-fishing. Federal, state, and tribal biologists worked together to estimate TACs for lake whitefish *Coregonus clupeaformis* during 1979-1982. During this period, the stock assessment methods used in the treaty waters were evolving and constrained by limited data. Where possible, stock sizes were estimated by application of a simple age-structured model. Although there was no formal harvest policy, TACs were generally set near the estimated maximum sustainable yield with ad hoc adjustments to the TACs being made to account for perceptions of current stock size and past harvest levels (e.g., AHWG 1979).

The 1985 Consent Decree laid out a 15 year agreement between federal, state and tribal agencies for the allocation of fishery harvest between the parties. The Technical Fisheries Review Committee (TFRC) was created by the decree to assess stocks of important fish species. As part of this mandate,

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the TFRC recommended TACs for lake whitefish stocks within the ceded territory. Stock assessments produced for the TFRC were generally based on simple age-structured models (Clark and Smith 1984). The 1985 decree did not specify a harvest policy, but based on TTWG (1984) the TFRC adopted a policy to limit total mortality to specified levels less than 60 to 65%.

The 2000 Consent Decree was a new 20 year agreement that set guidelines for the management of important fish species, as well as allocating fishery harvest. As part of the new decree, the Technical Fisheries Committee (TFC) was formed, which serves many of the same functions as did the TFRC under the previous decree. Also at this time, COTFMA was reorganized as the Chippewa/Ottawa Resource Authority (CORA). Unlike the previous decree, a reference mortality rate for lake whitefish of 65% was specified, which partially defines a harvest policy. New methods for conducting lake whitefish stock assessments and projecting TACs and harvest regulating guidelines (HRGs) were developed during the negotiation period for the 2000 Consent Decree by an interagency modeling group. The decree specifies that a newly formalized Modeling Subcommittee (MSC) of the TFC should build upon the work of the interagency modeling group to continue the lake whitefish stock assessment program.

The new stock assessment methods used statistical catch-at-age models, which were created for each lake whitefish stock by the interagency modeling group and further developed by the MSC. These stock assessment models used catch-at-age and effort data from the commercial fisheries to estimate population abundances, mortality rates, fishery harvests, and other population parameters of interest. Estimated quantities from the assessment models were used to project each stock’s abundance and mortality rates into the future, and then TAC/HRGs were calculated from these projections using the reference mortality rate.

The 2000 Consent Decree established requirements governing the calculation of TAC/HRGs. The reference level of total annual mortality (65%) specified for lake whitefish plays a different role depending on whether the yield from a particular management unit is allocated entirely to the tribes (tribal unit) or partially allocated to the state (shared unit). For tribal units, 65% total mortality is viewed as an upper target level, and management actions by the tribes are intended to prevent this level from being exceeded on average. For shared units, 65% total mortality is treated as an upper limit and TACs are established so as to allocate the yield between the parties as specified in the decree. State and tribal management agencies are responsible for separately implementing management actions (e.g., limits on entry to the fishery, gear restrictions, size limits, and trip limits) to constrain fishery yield at or below levels specified by TACs. If state or tribal fishery harvest exceeded their TAC/HRG by 25% or more, either in a single year or over the course of five years, then that party’s TAC in the following year is reduced by the amount that the previous TAC was exceeded.

One of the complications of applying a reference mortality rate to the results of the new age-structured assessment models is that these models account for the fact that fishing mortality varies with age. The MSC chose a conservative solution to the problem for lake whitefish by further defining the reference mortality rate. First, for the reference mortality rate, the maximum total mortality across all exploited ages was not to exceed the specified value of 65% (for most units). In addition, the spawning stock biomass per recruit (SSBR) at this mortality schedule was required to be at least 20% of the calculated SSBR for the unfished stock. If the SSBR was below the 20% threshold, then the maximum total mortality was reduced until the resulting SSBR was at least 20% of the unfished SSBR.

Due to the rapid development and implementation of the stock assessment models, not all of the approaches used in the models have been fully evaluated. For example, there were numerous methods for modeling each of the biological processes represented within the models from which the MSC analysts could select. Once a particular method for modeling a process was chosen, reasonable parameter starting values and bounds for those parameters also had to be selected by the analysts. It was unknown how much these choices affected stock assessment results.

Therefore, our objective was to further evaluate the stock assessment models for lake whitefish in the 1836 treaty waters of Lake Huron, with a view toward suggesting possible improvements. As a first step to achieve this objective, we performed a general analysis of the models' sensitivity to changes in "known" inputs and model structure.

Methods

The 1836 treaty waters of Lake Huron were divided into five lake whitefish management units, each thought to contain a distinct lake whitefish stock (Figure 1). Separate stock assessment models were developed for each of the lake whitefish management units. It was assumed in the models that no significant movement of lake whitefish occurs between management units.

Stock assessment model description.–Here we provide an overview of the stock assessment models' general structure. Ebener et al. (2005) provide a detailed description of the models. All of the stock assessment models consisted of two basic submodels, a population submodel and an observation submodel. The population submodel described the population dynamics of the stock in terms of abundance-at-age excluding the first year and the first age in each remaining year:

$$N_{a+1,y+1} = N_{a,y} e^{-Z_{a,y}} ,$$

where $N_{a+1,y+1}$ was the number of fish in age $a+1$ and year $y+1$ and $Z_{a,y}$ was the total instantaneous mortality rate in age a and year y. Numbers-at-age in the first year were estimated as a series of deviations in relative population abundance (i.e., one for each age) that were constrained to sum to zero. A population scaling parameter then converted these relative deviations to actual numbers-at-age. Numbers of fish in the first age of each year also were estimated as a series of scaled deviations using the same population scaling parameter, but were penalized for deviating too greatly from a Ricker stock-recruitment function:

$$N_{a_0,y} = \alpha G_{y-a_0-1} - e^{-\beta G_{y-a_0-1}} ,$$

where $N_{a_0,y}$ was the number of fish in the first age a_0 and year y, G_{y-a_0-1} was the number of eggs produced a_0-1 years prior to year y, α was the productivity parameter, and β was the density dependent parameter. The number of eggs was calculated within the submodel, based on a constant weight-specific fecundity. The productivity and density dependent parameters of the stock-recruitment function were estimated within the submodel. Numbers-at-age were converted to biomass using observed mean weight-at-age data. Total mortality consisted of four component parts:

$$Z_{a,y} = M + M_{L,a,y} + F_{G,a,y} + F_{T,a,y} ,$$

where M was the natural mortality rate, $M_{L,a,y}$ was the sea lamprey induced mortality rate in age a and year y, $F_{G,a,y}$ was the gill net fishing mortality rate in age a and year y, and $F_{T,a,y}$ was the trap net fishing mortality rate in age a and year y. Natural mortality was assumed to be constant for all ages and years, and was estimated from a prior (to model fitting) value calculated using Pauly's equation (Pauly 1980). Sea lamprey mortality was calculated externally to the model based on observed sea lamprey wounding rates. Fishing mortality was estimated by relaxing the assumption of fully separable fishing mortality (i.e., age-specific gear selectivity and year-specific fishing effort) and allowing gear selectivity to vary with time:

$$F_{i,a,y} = S_{i,a,y} q_i E_{i,y} \zeta_{i,y} ,$$

where $S_{i,a,y}$ was the gear selectivity of age a fish in fishery i and year y, q_i was the catchability in fishery i, $E_{i,y}$ was the observed fishing effort in fishery i and year y, and $\zeta_{i,y}$ was the deviation in fishing mortality from direct proportionality to observed fishing effort in fishery i and year y. Selectivity was estimated with a double logistic function of age, and one of the parameters of the function was allowed to change with time according to a quadratic function. This allowed age-specific selectivity to change gradually over time. An adjustment factor was applied to the observed gill net effort in order to account for changes in net height (i.e., the number of meshes deep) over time.

The observation submodel predicted catch-at-age for the gill net and trap net fisheries. Catch-at-age was predicted using Baranov's catch equation:

$$C_{i,a,y} = \frac{F_{i,a,y}}{Z_{a,y}} N_{a,y} \left(1 - e^{-Z_{a,y}}\right),$$

where $C_{i,a,y}$ was the number of age a fish caught in fishery i during year y, and all of the other parameters were estimated in the population submodel. Predicted catch-at-age was converted to a total annual catch and a proportion of catch-at-age for each fishery. An underreporting factor, measured as the proportion of the actual catch that was reported by fishers, was applied to the total catch to account for underreporting of landings and discards in the fisheries. The underreporting factor was obtained by comparing reported fishery landings to actual sales.

The parameter values providing the best fit were found using a Bayesian-based likelihood method (i.e., non-uniform or "informative" prior densities were assigned to some parameters). In particular, best fit parameter estimates maximized the joint posterior density, and for computational reasons this was done by finding parameter values that minimized the weighted sum of the negative log likelihoods and the negative log prior densities for the parameters with informative priors. Separate likelihood components were calculated for gill net total catch, gill net proportion of catch-at-age, trap net total catch, and trap net proportion of catch-at-age. Total annual catch was assumed to follow a lognormal distribution, with the negative log likelihood (ignoring some additive constants) given by:

$$L(C_i) = \frac{1}{2\sigma_i^2} \sum_{y=1}^{n} \left[\left(\ln \frac{C_{i,y}}{\hat{C}_{i,y}} \right)^2 \right] + n \ln \sigma_i ,$$

where σ_i was the standard deviation for log-scale observed total catch in fishery i, $C_{i,y}$ was observed total numbers of fish caught in fishery i and year y, $\hat{C}_{i,y}$ was predicted total numbers of fish caught in fishery i and year y, and n was the total number of years included in the model. Observed catch was reported as a weight, which was converted to numbers of fish using the observed mean weight of a harvested fish. Proportion of catch-at-age was assumed to follow a multinomial distribution, with the negative log likelihood (ignoring some additive constants) expressed as:

$$L(P_i) = -\sum_{y=1}^{n} N_{E,i,y} \sum_{a=1}^{m} \left(P_{i,y,a} \ln \hat{P}_{i,y,a} \right),$$

where $N_{E,i,y}$ was the effective number of fish used to calculate the age composition in fishery i and year y (Fournier and Archibald 1982), $P_{i,y,a}$ was the observed proportion of catch-at-age a in fishery i and year y, $\hat{P}_{i,y,a}$ was the predicted proportion of catch-at-age a in fishery i and year y, n was the total number of years included in the model, and m was the total number of ages included in the model.

In addition to the likelihood components, the objective function included terms related to prior densities for some of the parameters. First, deviations of predicted recruitments from the Ricker stock-recruitment function were assumed to follow a lognormal distribution. Second, deviation of predicted natural mortality from the prior natural mortality value (i.e., the Pauly's equation value) was assumed to follow a lognormal distribution. Third, deviations in the fishing mortality from direct proportionality to observed fishing effort were assumed to follow a lognormal distribution.

Each of the four likelihood components and three prior density terms were weighted by an emphasis factor as described by Methot (1990). If all likelihood components, prior densities, and their associated standard deviations or effective sample sizes were correctly specified, then the emphasis factors should all be 1.0. If there were any misspecifications of the standard deviations or effective sample sizes, then the emphasis factors provide a simple way for analysts to adjust how closely the model attempts to fit observed and predicted data for each likelihood component.

Projection model description.–Recommended yields for a reference (sometimes called target) mortality rate were calculated using stock assessment model outputs in a projection model. The stock assessment model outputs included estimated numbers-at-age, estimated total mortality, estimated natural mortality, and assumed sea lamprey mortality, all from the last year of the model, as well as, estimated trap net and gill net mortality rates that were averaged over the last three years of the model, and estimated average recruitment (over the last ten years) of the model. Along with the stock assessment model outputs, observed weight-at-age in the fisheries, observed mean proportion of females in the population, observed maturity schedules (represented as year and age-specific proportions), and observed time of year of spawning (represented as a proportion of the year) were also used in the projection model for SSBR calculations.

The projection model took the abundance-at-age estimates from the beginning of the last year of the stock assessment model, projected abundance to the beginning of the year for which recommended yields were desired, then projected yields for the trap net and gill net fisheries. Trap net and gill net fishery multiplier parameters were used to adjust age-specific fishing mortality rates by the same proportion for each age. The values of the two multipliers were set so as to achieve the reference mortality rate, while maintaining a desired allocation between trap net and gill net yields. There were two steps to determine appropriate values for the multipliers, which corresponded to how the reference mortality was defined. First, the multipliers were adjusted so that the maximum total annual mortality for any age did not exceed the reference (typically 65%). Second, the ratio of SSBR at this mortality schedule to SSBR without fishing was calculated (hereafter the SSBR ratio). If this ratio was less than 0.2, then the multipliers were decreased until the SSBR ratio equaled 0.2.

Sensitivity analysis.–Sensitivity analysis quantifies the effect of changes made to a model's input values and underlying assumptions on the model's output (Morgan and Henrion 1990). Our sensitivity analysis tested changes to the stock assessment models' input quantities and model structure (i.e., underlying model assumptions). Changes to observed input data represented possible changes in data collection (e.g., collecting more or fewer data), while changes to input values based on expert judgment (e.g., parameter starting values) represented changes made by the analyst during the model fitting process. Changes in model structure were based on alternative modeling procedures suggested in the literature. A complete list of the changes we evaluated is provided in Appendix A. Models for stocks in management units WFH-01, WFH-02, WFH-04, and WFH-05 were analyzed. The WFH-03 management unit model was not included in the following analysis, due to our inability to obtain satisfactory model convergence.

The stock assessment models were tested for their sensitivity to changes in input values. The observed mean weight-at-age of harvested fish was first increased then decreased for all ages at once by 10% of the baseline values. The year- and age-specific maturity schedule was varied by reassigning maturity values from each age to the next oldest age (e.g., maturity values for age 4 fish became the maturity values for age 5 fish). Then the first age was given a maturity value of zero. Similarly, the maturity schedule was varied by reassigning maturity values from each age to the next youngest age (e.g., maturity values for age 4 fish became the maturity values for age 3 fish), and setting the maturity in the last age equal to 1.00. Fecundity was adjusted by making it a linear function of average weight-at-age at the time of spawning. The gill net adjustment factors for net height were set equal to 1.00 to test the overall effect of the adjustments. The gill net adjustment factors also were varied by assuming the trend in the factors over time was alternatively more and less extreme than originally thought:

$$x_y = \bar{x} + c\left(x_{0,y} - \bar{x}\right),$$

where x_y was the new adjustment factor in year y, $\bar{x}$ was the average of the baseline adjustment factors across all years, $x_{0,y}$ was the baseline adjustment factor in year y, and scalar c alternatively equaled 0.8 to represent a less extreme trend and 1.2 to represent a more extreme trend. The underreporting factors were set to 1.00 for one fishery at a time to test the overall effect of the adjustments. Then, underreporting factors were increased and decreased by a value of 0.2 for one fishery at a time. The average proportion of females in the population was set to 0.5. The average proportion of females also was increased and decreased by a value of 0.2. The time of year of spawning was increased and decreased by a value of 0.2. Bounds for each model parameter, which limited the range of values a given parameter could take, were widened one at a time by decreasing the lower bound by 20% of the baseline value and increasing the upper bound by 20% of the baseline value. Bounds for each model parameter were narrowed one at a time by increasing the lower bound by 20% of the baseline value and decreasing the upper bound by 20% of the baseline value. Starting values for each model parameter were increased and decreased one at a time by 20% of the baseline values. Natural mortality was altered by fixing the parameter to the starting value and by increasing and decreasing the starting value by 20%.

The stock assessment models were tested for their sensitivity to changes in model structure. Recruitment in each year was estimated as a free parameter without any penalty for deviating from stock-recruitment model predictions. Also, a Beverton-Holt stock-recruitment function, rather than a Ricker stock-recruitment function, was used to predict recruitment. The Beverton and Holt (1957) stock-recruitment function was:

$$N_{a_0,y} = \frac{\alpha G_{y-a_0-1}}{1+\beta G_{y-a_0-1}},$$

where all of the variables are defined the same as in the Ricker stock-recruitment function. In the baseline assessment models, predicted total annual catches in numbers of fish were fit to observed total annual catches in numbers of fish in the objective function. The observed biomass of fish caught was converted to numbers of fish caught using the mean weight-at-age of a harvested fish. As an alternative approach, predicted total annual catches in biomass of fish were fit to observed total annual catches in biomass of fish in the objective function. The predicted numbers of fish caught, calculated from Baranov's catch equation, were converted to biomass of fish caught using the mean weight-at-age of a harvested fish. The likelihood component emphasis factors were doubled and halved one at a time. Gamma likelihood components were substituted for all lognormal likelihood components, keeping the same coefficient of variation:

$$L(C_i) = -\phi_i \sum_{y=1}^{n} \left[\ln\left(\frac{C_{i,y}}{\hat{C}_{i,y}} \right) - \frac{C_{i,y}}{\hat{C}_{i,y}} \right],$$

where ϕ_i was the inverse of the squared coefficient of variation for observed harvest in fishery i (Cadigan and Myers 2001) and the other variables were the same as in the lognormal likelihood component. Dirichlet likelihood components were substituted for all multinomial likelihood components, with fixed parameters setting the effective sample size to equal 100:

$$L(P_i) = \sum_{y=1}^{n} \left[\ln\Gamma\left(\sum_{a=1}^{m} \gamma_i \hat{P}_{i,y,a} \right) - \sum_{a=1}^{m} \ln\Gamma\left(\gamma_i \hat{P}_{i,y,a}\right) + \sum_{a=1}^{m} \left(\gamma_i \hat{P}_{i,y,a} - 1\right) \ln P_{i,y,a} \right],$$

where γ_i represented the effective sample size for fishery i, Γ was the gamma function, and the other variables were the same as in the multinomial likelihood component.

Each stock assessment model was rerun for each of the changes tested. In order to better specify the standard deviation around the stock recruitment relationship, an initial recruitment standard deviation was input into the model. The standard deviation of predicted recruitment was then calculated at the conclusion of model fitting. The predicted recruitment standard deviation then replaced the former input standard deviation, and the model was rerun leading to a new predicted recruitment standard deviation. This process was repeated 50 times with the goal of getting the ratio between input recruitment standard deviation and predicted recruitment standard deviation as close to unity as possible. After the 50 runs, the model was considered to have converged to a satisfactory solution if: 1.) the ratio of recruitment standard deviations was between 0.98 and 1.02; 2.) the maximum gradient component, which measures the maximum amount of change in parameter estimates during model fitting, was less than 1×10^{-2}; and 3.) the Hessian matrix, which is used to calculate standard deviations for the parameter estimates, was positive definite.

The sensitivity of the stock assessment models to change was monitored by tracking several of the models' output quantities. The output quantities of interest included: the estimated gill net and trap net fishing mortality rates for fish fully selected to the gear averaged over the last three years of the assessment, estimated population biomass averaged for the last three years of the assessment, estimated SSBR of the unfished population, predicted SSBR at reference mortality levels, estimated SSBR ratio, and the estimated yield calculated for reference mortality rates for the projected population. Model sensitivity was calculated as the percent difference of the evaluation quantity of the adjusted model from the baseline value of the evaluation quantity of the baseline model (Table 1):

$$D_{\%} = \frac{\theta' - \theta_0}{\theta_0} \times 100,$$

where $D_{\%}$ was the percent difference, θ_0 was the baseline value of the evaluation quantity, and θ' was the value of the evaluation quantity from the adjusted model.

Results

All of the stock assessment models were sensitive to changes in the input values. Increasing observed mean weight-at-age of a harvested fish led to an increase in the projected TAC/HRG in all of the projection models except for the WFH-05 gill net fishery (Table 2). Likewise, decreasing mean weight-at-age led to a decrease in the projected TAC/HRG in all of the projection models except for the WFH-05 gill net fishery. Changes in mean weight-at-age of a harvested fish in the gill net fishery had no effect upon the projected TAC/HRG in the WFH-05 model, due to the small size of the gill net fishery in that management unit. These effects upon projected TAC/HRGs were greater for the gill net fishery in WFH-01 and WFH-04, and were greater for the trap net fishery in WFH-02. Mean weight-at-age influences projected TAC/HRGs because the TAC/HRGs are calculated as biomass of fish.

Unexpectedly, setting gill net effort adjustment factors for net height to one, and increasing or decreasing gill net effort adjustment factors increased the projected WFH-02 TAC/HRG by 34.7% and changed the remaining evaluation quantities to a lesser degree (-0.4 to 4.6%), except for SSBR of the unfished population which was unaffected (Table 2). For the other three models, changes to gill net effort adjustment factors had slight effects (-3.3 to 2.8%) on all of the evaluation quantities, except for SSBR of the unfished population, though no clear patterns were apparent. The WFH-01 model failed to converge when gill net effort adjustment factors were set equal to one.

Shifting the maturity schedule later by one age led to substantial decreases (-48.2 to -21.2%) in the SSBR of the unfished population and SSBR at the reference mortality schedule (Table 3). There was a greater decrease in SSBR at the reference schedule, because the fish were maturing later after more mortality had occurred. The greater decrease in SSBR at reference mortality schedule led to a decrease in the SSBR ratio. Likewise, shifting the maturity schedule earlier by one age led to substantial increases (13.6 to 55.4%) in the SSBR of the unfished population, SSBR at the reference mortality schedule, and the SSBR ratio in all of the models except WFH-02, due to the resulting increase in spawning biomass. The WFH-02 model failed to converge when the maturity schedule was shifted earlier by one age. Shifting the maturity schedule later by one age increased the projected TAC/HRG (0.9 to 38.5%) in all of the models. Changes in the maturity schedule also had modest influence on gill net and trap net mortality, and biomass (-2.8 to 5.9%) in all of the models. This influence of the maturity schedule on the evaluation quantities is due to the fact that maturity schedule values are used to calculate the number of eggs produced for the stock-recruitment function, and this affects the objective function.

Setting the average proportion of females in the population equal to 0.5 led to an increase (21.8 to 31.6%) in SSBR of the unfished population and SSBR at the reference mortality schedule in all of the models, except the WFH-04 model which failed to converge (Table 3). Increasing the proportion of females led to an increase (47.9 to 52.6%) in SSBR of the unfished population and SSBR at the reference mortality schedule in all of the models, because the spawning stock was considered to be the mature females within the population. Decreasing the proportion of females led to a decrease (-52.6 to -48.9%) in SSBR of the unfished population and SSBR at the reference mortality schedule in all of the models, due to the resulting decrease in spawning stock. All of the adjustments made to the proportion of females led to slight changes (-0.6 to 5.4%) in the fishing mortalities, biomass, and SSBR ratio; and larger changes (23.8 to 37.2%) in the projected TAC/HRG for the WFH-02 model.

Increasing the time of year of spawning led to a decrease (-12.4 to -2.7%) in SSBR of the unfished population, SSBR at the reference mortality schedule, and SSBR ratio because fewer fish survived to spawn later in the year (Table 3). Increasing the time of year of spawning also led to an increase (0.3 to 36.2%) in the projected TAC/HRG for all of the models because the spawning stock was exposed to the fisheries for a longer period of time before spawning. Decreasing the time of spawning led to an increase (2.8 to 14.5%) in SSBR of the unfished population, SSBR at the reference mortality schedule, and SSBR ratio because more fish would survive to spawn earlier in the year. Decreasing the time of spawning also led to a decrease (-1.1 to -0.4%) in the projected TAC/HRG for all of the models because the spawning stock was exposed to the fisheries for a shorter period of time, except in the WFH-02 model which had an unexpected increase of 33.0% in the TAC/HRG. Adjustments to the time of spawning led to slight changes (-0.8 to 5.1%) in the fishing mortalities and biomass with no clear pattern in all of the models. These slight changes appeared because time of spawning is used to calculate the number of eggs produced for the stock-recruitment function, which influenced the objective function.

Increasing trap net fishery underreporting adjustment factors led to increases in trap net mortality (12.8 to 18.1%) accounting for the increased trap net harvest in all models, except for WFH-05 (-1.3% decrease), and decreases in gill net mortality (-22.3 to -7.6%; Table 4). Decreasing trap net fishery underreporting adjustment factors led to decreases in trap net mortality (-13.4 to -10.7%) due to the lower trap net harvest, except for an increase of 1.1% in trap net mortality in the WFH-05 model, and increases in gill net mortality (5.5 to 22.6%). Likewise, increasing gill net fishery underreporting adjustment factors led to increases in gill net mortality (6.8 to 29.8%) and decreases in trap net mortality (-16.7 to -13.4%) due to increased gill net harvest, except for a 1.8% increase in trap net mortality in the WFH-05 model. Decreasing gill net fishery underreporting adjustment factors led to decreases in gill net mortality (-18.7 to -6.1%) and increases in trap net mortality (10.3 to 14.5%) due to decreased gill net harvest, except for a decrease of -1.2% in trap net mortality in the WFH-05 model. The small, but unforeseen, changes in fishing mortality rates (< 2%) in the WFH-05 model appeared to be due to the small gill net fishery, which effectively makes WFH-05 a one (trap net) fishery system. It appears the WFH-05 assessment model accounted for adjustments in observed trap net harvest by making large changes to the biomass and small changes to fishing mortality. Changes in gill net harvest led to only small adjustments of the biomass and trap net fishing mortality because of the small size of the fishery. Changes in the fishery underreporting adjustment factors also affected biomass (-18.3 to 28.5%), SSBR at the reference mortality schedule (-4.4 to 3.8%), and SSBR ratio (-4.4 to 3.8%), though no patterns were apparent. Changes in the fishery underreporting adjustment factors had no effect on the SSBR of the unfished population.

Both widening and narrowing the parameter bounds for natural mortality had little or no effect on the WFH-01, WFH-04, and WFH-05 models, but led the WFH-02 model to converge to the same solution, different from the baseline one, where trap net mortality decreased by -0.2%, gill net mortality increased by 1.2%, biomass increased by 4.6%, SSBR of the unfished population remained unchanged, SSBR and SSBR ratio decreased by -0.1%, and projected TAC/HRG increased by 34.7% (Table 5). This alternate solution was very similar to the one reached by the model for this unit when changes were made to the gill net effort adjustment factors.

Narrowing trap net catchability bounds and widening and narrowing gill net catchability bounds in the WFH-02 model led to the same alternate solution described above, where projected TAC/HRG increases by 34.7% while all the other evaluation quantities, except for SSBR of the unfished population, changed from -0.2 to 4.6% (Table 6). Increasing and decreasing the trap net catchability starting value and increasing the gill net starting value again led to the same alternate solution for WFH-02 with the 34.7% increase in projected TAC/HRG. None of the other models showed any sensitivity to changes in the catchability parameters.

Widening and narrowing the population scaling parameter’s bounds, and decreasing the population scaling parameter’s starting value led to the state with the 34.7% increase in projected TAC/HRG in the WFH-02 model (Table 7). Narrowing the relative population deviation parameters’ bounds led to a 31.9% increase in gill net mortality, a 25.2% increase in the projected TAC/HRG, and smaller changes (2.2 to 8.0%) in trap net mortality, biomass, and SSBR and SSBR ratio in the WFH-02 model. The other models were unaffected by changes to the population scaling parameter and relative population deviation parameters.

Widening the bounds of the Ricker stock-recruitment function's productivity parameter led to a 37.2% increase in projected TAC/HRG and smaller changes (-0.4 to 5.4%) in the fishing mortalities and biomass in the WFH-02 model (Table 8). Narrowing the bounds of the Ricker function's productivity parameter led to changes (-9.2 to 10.8%) in all of the evaluation quantities, except for SSBR for the unfished population, for the WFH-01 and WFH-05 models. The WFH-02 model failed to converge when the Ricker function's productivity parameter's bounds were narrowed and starting value were decreased. Widening the bounds of the Ricker function's density dependence parameter, increasing the starting value of the productivity parameter, and increasing and decreasing the starting value of the density dependence parameter led to the state where the projected TAC/HRG increases by 34.7% in the WFH-02 model. Narrowing the bounds of the Ricker function's density dependence parameter led to a -43.4 to -20.6% decrease in the projected TAC/HRG and smaller changes (-15.2 to 3.0%) in the remaining evaluation quantities, except for SSBR of the unfished population, for the WFH-01 and WFH-04 models.

Widening the bounds of the gill net selectivity function's first inflection point and narrowing the bounds of the gill net selectivity function's first slope parameter led to the state with the 34.7% increase in the projected TAC/HRG in the WFH-02 model (Table 9). Narrowing the bounds of the gill net selectivity function's first inflection point led to changes (-15.4 to 14.7%) in all of the evaluation quantities, except SSBR of the unfished population, in the WFH-02 and WFH-04 models. The WFH-02 model failed to converge when the bounds on the gill net selectivity function's second inflection point were widened. Narrowing the bounds of the trap net selectivity function's first inflection point led to changes (-17.0 to 18.1%) in all of the other evaluation quantities, except for SSBR of the unfished population, in the WFH-04 model (Table 10). The WFH-01 model failed to converge when the starting value for the gill net selectivity function's second slope parameter was increased. Increasing and decreasing the starting values for the gill net selectivity function's first and second inflection points, decreasing the starting values for the gill net selectivity function's first and second slope parameters, decreasing the starting value for the trap net selectivity function's first inflection point, increasing and decreasing the starting value for the trap net selectivity function's second inflection point, and decreasing the starting value for the trap net selectivity function's second slope parameter led to the alternate state with the 34.7% increase in the projected TAC/HRG in the WFH-02 model. The WFH-02 model failed to converge when the starting value for the trap net selectivity function's first inflection point was increased. The WFH-04 model failed to converge when the starting value for the gill net selectivity function's first inflection point was decreased. Adjustments to the starting values for the gill net selectivity function's parameters led to -40.5 to 131.0% changes in trap net mortality, -64.6 to 1,277.2% changes in gill net mortality, -50.9 to 44.6% changes in biomass, -5.8 to 14.4% changes in SSBR and SSBR ratio, -87.7 to 41.7% changes in projected TAC/HRG, and no change to SSBR for the unfished population for the WFH-05 model. Increasing the starting value for the trap net selectivity function's second inflection point, and increasing and decreasing the starting value for the trap net selectivity function's second slope parameter led to a change (-0.1 to 0.1%) in trap net mortality for the WFH-01 model. Decreasing the starting value for the trap net selectivity function's second inflection point led to changes (-0.4 to 0.1%) in all of the evaluation quantities, except for SSBR of the unfished population, for the WFH-01 model.

Increasing and decreasing the likelihood emphasis factor for natural mortality led to the alternate solution with a 34.7% increase in the projected TAC/HRG for the WFH-02 model (Table 11). The WFH-01 model failed to converge when the trap net catch and age composition emphasis factors were increased. The WFH-04 model failed to converge when the trap net catch emphasis factor was increased, and when the trap net and gill net age composition emphasis factors were decreased. All the remaining adjustments to the likelihood emphasis factors led to positive and negative changes (-17.3 to 62.0%) that showed no pattern in all of the evaluation quantities, except SSBR of the unfished population, for all of the models.

All of the stock assessment models also were sensitive to changes in model structure. Holding natural mortality constant at its starting value in the WFH-02 model led to the state with the 34.7% increase in projected TAC/HRG (Table 12). Modeling fecundity as a linear function of weight led to changes (-5.1 to 38.8%) in all of the evaluation quantities, except for SSBR of the unfished population, for the WFH-01, WFH-02, and WFH-05 models, because fecundity was used to calculate the number of eggs produced (stock size) for the stock-recruitment function. The WFH-04 model failed to converge when fecundity was modeled as a linear function of weight.

Estimating each year's recruitment as a free parameter led to changes (-3.8 to 39.8%) in all of the evaluation quantities, except for SSBR of the unfished population, for the WFH-02 and WFH-05 models (Table 12). The WFH-01 and WFH-04 models failed to converge when recruitment was estimated as free parameters. Estimating recruitment using a Beverton-Holt stock-recruitment model led to (-10.0 to 54.3%) changes in all of the evaluation quantities, except for SSBR of the unfished population, in all of the models.

Fitting biomass, instead of numbers, of fish caught in the objective function led to changes (-10.2 to 39.6%) in all of the evaluation quantities, except for SSBR of the unfished population, for the WFH-02, WFH-04, and WFH-05 models (Table 12). The WFH-01 model failed to converge when the mass of fish caught was used in the objective function.

The use of the gamma likelihood function in place of the lognormal likelihood function led to small changes (-0.3 to 0.7%) in all of the evaluation quantities, except for SSBR of the unfished population, in the WFH-01, WFH-04, and WFH-05 models (Table 12). The WFH-02 model failed to converge when the gamma likelihood function was used. The use of the Dirichlet likelihood function in place of the multinomial likelihood function led to changes (-18.0 to 25.9%) in all of the evaluation quantities, except for SSBR of the unfished population, for all of the models.

Most of the adjustments made to the models led to negative log-likelihood values that were the same as, or higher than, the baseline likelihood values, which means that the model fit was not improved. In particular, the alternate solution often arrived at by the WFH-02 model had a higher likelihood value (4,340.5) than the baseline model (4,337.6). There were, however, several changes that led to a decrease in the negative log-likelihood value, which means that the changes produced parameter estimates that fit the data better than the baseline parameter estimates. In particular a better fit was obtained after decreasing the bounds of the Ricker recruitment function's density dependence parameter in the WFH-01 and WFH-04 models and after decreasing the starting value of the gill net selectivity function's second slope parameter in the WFH-05 model (Table 13). These instances of better model fit could be due to random chance given the large number of model changes explored. Likelihood values could not be directly compared to determine better model fit in cases where the model structure was changed or when the likelihood emphasis factors were adjusted, because these changes altered the objective function.

Discussion

We performed a simple sensitivity analysis of the stock assessment models for lake whitefish in the 1836 treaty waters of Lake Huron to changes in input quantities and model structure. The changes we tested could be divided into two alternate categories that affect the way in which the results are interpreted. First, changes to the observed data and model structure led to changes in the objective function (negative log-likelihood) and thus altered the optimal solution (i.e., the best-fit parameter estimates) from the optimal solution of the baseline model. In this case, changes in the output quantities represent the model seeking the new optimal solution. Second, changes to the parameter starting values and parameter bounds did not alter the optimal solution from the optimal solution of the baseline model. In this case, changes in the output quantities mean that the model has become trapped at a local minimum for the objective function or found the true global minimum for the objective function depending upon whether the likelihood value is greater than or less than, respectively, the baseline model's likelihood value. The danger of becoming trapped at a local minimum is that the estimates of important management quantities (e.g., TAC/HRG) would not be the most probable estimates given the existing assessment model and data. In other words, management decisions resulting from such a stock assessment would be based on an incorrect picture of the stock given the best available science.

A simple sensitivity analysis, like the one conducted here, can be useful for identifying models that are unstable and highly sensitive to change. The WFH-02 stock assessment model appears to be such a sensitive model. Thirty-five of the 111 changes tested led the model to converge to an alternate solution, which provided a poorer fit between observed and predicted values than the baseline model. The alternative solution was similar to the baseline model's solution except for a large increase in the projected TAC/HRG, due to a change in the estimated selectivity patterns. It appears that the WFH-02 model can easily become trapped at a local minimum for the objective function, which leads to this alternate solution, rather than finding the "true" global minimum. Besides identifying unstable models, sensitivity analysis can also provide clues for analysts as they seek the best fit for an unstable model. Sensitivity analysis can reveal to which parameters of the model important outputs are most sensitive to change. We encourage analysts to try a wide range of starting values and bounds for those parameters to help ensure that the global minimum for the objective function is found each time the model is updated. To this end, we have created a program for the MSC to automate our sensitivity analysis, using AD Model Builder software (ADMB 2002). This program will allow analysts to more easily evaluate the sensitivity of the stock assessment models whenever the models are updated.

All of the stock assessment models were sensitive to changes in the stock-recruitment function's parameter bounds. Narrowing the density dependence parameter bounds led to better fit parameter estimates for the WFH-01 and WFH-04 models, which significantly reduced the projected TAC/HRG in both models. It appears particularly important to do sensitivity analysis using a range of starting values and bounds for recruitment parameters each time the models are updated.

Sensitivity analysis also can reveal patterns of sensitivity across models, which may point to assumptions about underlying basic model structure (i.e., the way various biological, fishery, and data producing processes are included in the models) that should receive more attention. We found that the Lake Huron stock assessment models were sensitive to our assumptions embodied in stock-recruitment functions, gear selectivity, and assumed probability distributions used to define the likelihood functions. Of particular importance, the WFH-02 and WFH-04 model evaluation quantities underwent similar changes, which resulted in increased TAC/HRGs, when the Beverton-Holt recruitment function was used. A number of authors have considered the consequences of assuming different stock-recruitment relationships to the management advice stemming from those assumed relationships (Myers et al. 1994; Barrowman and Myers 2000). Other authors have discussed the relative merits of estimating stock-recruitment parameters inside stock assessment models versus outside them (Maunder and Deriso 2003). The issue here is somewhat different than is addressed in that work since we are only considering short-term projections. Our concern here is more whether including stock-recruitment functions as "prior" information influences and potentially improves our estimates and resulting short-term management advice, given that a harvest policy exists. A simulation study, where either freely estimated recruitment or priors based on different recruitment functions were used would allow for a more detailed analysis of how different approaches to estimation of recruitment fare.

We did not explicitly consider alternative approaches to estimating selectivity. However, all of the models showed sensitivity to changes in gear selectivity starting values and parameter bounds. While sometimes the changes were small, in other cases changes were pronounced (e.g., WFH-02 and WFH-05). These results reinforce concerns that have arisen about the general suitability of the current double logistic selectivity function during the development of the stock assessment models. As a result of problems encountered during development of the baseline models, all the selectivity parameters are estimated in only one of the Lake Huron lake whitefish assessment models (WFH-01). In each of the other models, some of the selectivity parameters must be held constant in order for the models to converge on a solution. Thus, issues clearly go beyond simply finding the best starting values and parameter bounds. Reduced or constrained versions of the double logistic are not the only alternatives. For example, logistic curves (Punt et al. 2001), double logistic curves (Methot 1990), gamma-type functions (Deriso et al. 1985), and polynomials (Fournier 1983) have all been used to model selectivity. Kimura (1990) and Radomski et al. (2005) found that use of an inappropriate selectivity function can greatly increase the error in modeling results. This is another area where a simulation study could be used to help evaluate the current and alternative approaches to modeling selectivity. Alternatively, an empirical selectivity experiment could be used to determine the actual gear selectivity, but this would need to be done for both gill nets and trap nets.

All of the models showed some sensitivity to changes in the negative log likelihood function, both when likelihood emphasis factors were altered and when alternate distributional assumptions were made. In theory, if the assumed standard deviations for the natural mortality, catch, and effort data and the assumed maximum effective sample sizes for the age composition data are correct, then all of the likelihood emphasis factors should be set to one. Methot (1990) warns that sensitivity to changes in the emphasis factors indicates that there is some inconsistency between the data sources or that some process has not been modeled correctly. Sensitivity analysis of the models to the likelihood emphasis factors should be tested whenever the emphasis factors are adjusted during model updates in order to report this sensitivity along with model results. Replacing the lognormal likelihood function with the gamma likelihood function led to only small changes in evaluation quantities. Cadigan and Meyers (2001) found similar results when comparing the two likelihood functions, although they emphasized that the gamma likelihood function is more robust to invalid distributional assumptions than the lognormal. Williams and Quinn (2000a, 2000b) successfully used the Dirichlet likelihood function to represent age composition data for Pacific herring, where sample sizes were large. Replacing the multinomial likelihood function with the Dirichlet likelihood function led to some changes in the evaluation quantities, particularly the TAC/HRGs, in all of the models. Again we believe a simulation study could be used to evaluate the robustness of assessments based on these alternative distributions, and to evaluate potential approaches to selecting among them.

In conclusion, we recommend that a sensitivity analysis be run every time either a model is updated with new data or when a model’s structure is changed to ensure that the optimal parameter estimates have been obtained. Such a sensitivity analysis would not need to evaluate each of the model changes presented in this report, and could focus simply on changes to parameter bounds and starting values. This sensitivity analysis would be especially important for unstable models such as the WFH-02 model. If an unstable model or sensitive model process is identified in such an analysis, we recommend that in the short term a wide range of parameter starting values and bounds be tested to ensure that the optimal parameter estimates are found. For a long term solution, we recommend that such unstable models or sensitive model processes be reparameterized (i.e., that alternative methods for modeling these processes be used) to increase model stability. To that end, we also recommend that alternative stock-recruitment functions, gear selectivity functions, and likelihood distributional assumptions be evaluated in more detail. Monte Carlo simulation studies could be used to compare the performances of alternative models, as well as identify appropriate methods for choosing between alternative models. We believe that identifying model selection methods is important, because they would allow analysts to evaluate new modeling approaches as they become available.

Acknowledgments

We would like to thank D. Hayes, M. Jones, and G. Rosa from Michigan State University, as well as, P. Schneeberger of the Michigan Department of Natural Resources for their comments which have improved this report. This report is publication 2008-25 of the Quantitative Fisheries Center at Michigan State University. This project was funded through studies 230713 and 236102 of the Michigan Department of Natural Resources, with funding from U.S. Fish and Wildlife Service, Sport Fish Restoration, Project F-80-R. This research was completed in partial fulfillment of the requirements for a Doctor of Philosophy degree at Michigan State University.

Figure 1.–1836 treaty-ceded waters and lake whitefish management units in lakes Huron, Michigan and Superior.

Table 1.–Predicted values for trap-net mortality (TN F), gill-net mortality (GN F), population biomass (lbs), spawning stock biomass per recruit (SSBR) for unfished population, SSBR at reference mortality schedule, SSBR ratio, projected total allowable catch (TAC) or harvest regulating guideline (HRG; lbs), and the negative log-likelihood values from the original (unmodified) lake whitefish stock assessment models for the 1836 treaty-ceded waters of Lake Huron in 2001. Fishing mortality values are for fish fully selected to the gear.

Model	TN F	GN F	Biomass	Unfished SSBR	Ref SSBR	SSBR ratio	TAC/HRG	Likelihood
WFH-01	0.07	0.37	2,397,250	0.38	0.12	0.31	374,829	6,410.34
WFH-02	0.59	0.25	2,000,810	0.63	0.28	0.44	146,597	4,337.59
WFH-04	0.24	0.35	2,341,150	0.42	0.13	0.30	333,149	5,694.84
WFH-05	0.35	0.003	4,776,130	0.34	0.17	0.49	874,957	2,987.65

Table 2.–Percent difference from baseline values for trap-net mortality (TN F), gill-net mortality (GN F), population biomass, spawning stock biomass per recruit (SSBR) for unfished population, SSBR at reference mortality schedule, SSBR ratio, projected total allowable catch (TAC) or harvest regulating guideline (HRG) from the lake whitefish stock assessment models (WFH-01, WFH-02, WFH-04, and WFH-05) for the 1836 treaty-ceded waters of Lake Huron in 2001, when data input values were increased (+), decreased (-), and set to specific values. Fishing mortality values are for fish fully selected to the gear. Some changes resulted in the models failing to converge (fc).

	TN F		GN F		Biomass		Unfished SSBR		Ref SSBR		SSBR ratio		TAC/HRG	
Description of change	+	-	+	-	+	-	+	-	+	-	+	-	+	-
WFH-01														
TN weight-at-age	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.6	-4.6
GN weight-at-age	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.4	-15.4
GN net height factor = 1.0	fc		fc		fc		fc		fc		fc		fc	
GN net height factor	-0.1	0.1	0.3	-0.4	0.0	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	-0.3	0.3
WFH-02														
TN weight-at-age	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.5	-16.5
GN weight-at-age	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.5	-3.5
GN net height factor = 1.0	0.7		1.3		4.1		0.0		-0.3		-0.3		34.7	
GN net height factor	-0.4	-0.1	1.1	1.3	4.6	4.5	0.0	0.0	-0.1	-0.1	-0.1	-0.1	34.7	34.6
WFH-04														
TN weight-at-age	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.1	-8.1
GN weight-at-age	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.0	-12.0
GN net height factor = 1.0	-1.4		-2.1		1.2		0.0		0.2		0.2		1.4	
GN net height factor	0.3	-0.3	0.5	-0.5	-0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0	-0.3	0.3
WFH-05														
TN weight-at-age	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.1	-20.0
GN weight-at-age	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GN net height factor = 1.0	-1.2		-3.3		2.8		0.0		1.1		1.1		2.3	
GN net height factor	0.3	-0.3	0.8	-0.8	-0.6	0.6	0.0	0.0	-0.3	0.3	-0.3	0.3	-0.5	0.5

Table 3.–Percent difference from baseline values for trap-net mortality (TN F), gill-net mortality (GN F), population biomass, spawning stock biomass per recruit (SSBR) for unfished population, SSBR at reference mortality schedule, SSBR ratio, projected total allowable catch (TAC) or harvest regulating guideline (HRG) from the lake whitefish stock assessment models (WFH-01, WFH-02, WFH-04, and WFH-05) for the 1836 treaty-ceded waters of Lake Huron in 2001, when data input values were increased (+), decreased (-), and set to specific values. Fishing mortality values are for fish fully selected to the gear. Some changes resulted in the models failing to converge (fc). For maturity schedule, an increase (+) means maturity values were shifted up to the next oldest age, while a decrease (-) means maturity values were shifted down to the next youngest age. The proportion of females in the population was set equal to 0.5, increased (+), and decreased (-) from the original value.

	TN F		GN F		Biomass		Unfished SSBR		Ref SSBR		SSBR ratio		TAC/HRG	
Description of change	+	-	+	-	+	-	+	-	+	-	+	-	+	-
WFH-01														
Maturity schedule	-0.2	0.3	-0.1	0.1	0.6	-0.9	-24.9	23.5	-48.2	53.5	-31.0	24.3	1.2	-1.8
Proportion females = 0.5	0.0		0.0		0.0		31.6		31.6		0.0		0.0	
Proportion females	0.0	0.0	0.0	0.0	0.0	0.0	52.6	-52.6	52.6	-52.6	0.0	0.0	0.0	0.0
Time of spawning	0.0	0.1	0.0	0.0	0.1	-0.2	-4.0	4.2	-11.0	13.1	-7.3	8.5	0.3	-0.4
WFH-02														
Maturity schedule	-0.5	fc	1.2	fc	5.9	fc	-21.2	fc	-37.2	fc	-20.3	fc	38.5	fc
Proportion females = 0.5	0.1		1.4		2.7		22.2		21.8		-0.4		28.9	
Proportion females	0.3	-0.4	1.3	1.1	1.2	5.4	48.9	-48.9	47.9	-48.9	-0.6	0.0	23.8	37.2
Time of spawning	-0.3	-0.1	1.1	1.3	5.1	4.0	-2.7	2.8	-7.4	8.2	-4.8	5.3	36.2	33.0
WFH-04														
Maturity schedule	-2.8	-2.1	-1.3	-0.1	2.7	3.9	-26.0	24.8	-43.2	55.4	-23.3	24.5	0.9	14.4
Proportion females = 0.5	fc		fc		fc		fc		fc		fc		fc	
Proportion females	0.0	0.0	0.0	0.0	0.0	0.0	50.0	-50.0	50.0	-50.0	0.0	0.0	0.0	0.0
Time of spawning	-0.6	0.2	-0.8	0.5	0.5	-0.1	-3.3	3.4	-12.4	14.5	-9.4	10.7	2.2	-1.1
WFH-05														
Maturity schedule	-2.2	1.9	-2.0	2.0	2.4	-2.4	-28.0	27.2	-40.5	44.5	-17.4	13.6	1.9	-1.9
Proportion females = 0.5	0.0		0.0		0.0		25.6		25.6		0.0		0.0	
Proportion females	0.0	0.0	0.0	0.0	0.0	0.0	50.3	-50.3	50.3	-50.3	0.0	0.0	0.0	0.0
Time of spawning	-0.7	0.6	-0.5	0.5	0.6	-0.6	-4.5	4.7	-9.9	11.3	-5.6	6.3	0.7	-0.7

Table 4.–Percent difference from baseline values for trap-net mortality (TN F), gill-net mortality (GN F), population biomass, spawning stock biomass per recruit (SSBR) for unfished population, SSBR at reference mortality schedule, SSBR ratio, projected total allowable catch (TAC) or harvest regulating guideline (HRG) from the lake whitefish stock assessment models (WFH-01, WFH-02, WFH-04, and WFH-05) for the 1836 treaty-ceded waters of Lake Huron in 2001, when data input values were increased (+), decreased (-), and set to specific values. Fishing mortality values are for fish fully selected to the gear. Trap-net (TN) and gill-net (GN) underreporting factors (i.e., proportion of actual catch reported) were set equal to 1.0, increased (+), and decreased (-) from the original values.

	TN F		GN F		Biomass		Unfished SSBR		Ref SSBR		SSBR ratio		TAC/HRG	
Description of change	+	-	+	-	+	-	+	-	+	-	+	-	+	-
WFH-01														
TN underreporting = 1.0	-6.8		0.8		-1.4		0.0		-0.1		-0.1		-3.3	
TN underreporting	-11.7	15.0	7.2	-9.7	-6.1	9.7	0.0	0.0	3.2	-4.4	3.2	-4.4	-8.7	14.3
GN underreporting = 1.0	6.8		-1.4		-5.2		0.0		-0.4		-0.4		-4.4	
GN underreporting	11.9	-14.7	-7.8	8.6	-11.4	18.0	0.0	0.0	-3.6	3.8	-3.6	3.8	-8.7	14.3
WFH-02														
TN underreporting = 1.0	-5.4		1.9		0.5		0.0		-0.7		-0.7		31.9	
TN underreporting	-10.7	12.8	7.4	-7.6	-8.1	24.6	0.0	0.0	-0.6	0.5	-0.6	0.5	22.9	53.5
GN underreporting = 1.0	5.3		-0.2		2.4		0.0		0.4		0.4		29.7	
GN underreporting	10.3	-13.4	-7.2	8.7	-4.3	13.5	0.0	0.0	0.7	-0.7	0.7	-0.7	-6.5	53.3
WFH-04														
TN underreporting = 1.0	-4.6		2.3		-2.6		0.0		-0.5		-0.5		-2.9	
TN underreporting	-13.4	18.1	5.5	-7.6	-5.8	9.1	0.0	0.0	0.0	0.2	0.0	0.2	-4.7	7.6
GN underreporting = 1.0	5.0		-2.6		-4.2		0.0		-0.1		-0.1		-5.5	
GN underreporting	14.5	-16.7	-6.1	6.8	-11.8	18.5	0.0	0.0	0.0	0.2	0.0	0.2	-13.2	20.9
WFH-05														
TN underreporting = 1.0	1.3		8.6		-7.6		0.0		-0.4		-0.4		-7.7	
TN underreporting	1.1	-1.3	22.6	-22.3	-18.3	28.5	0.0	0.0	0.0	0.1	0.0	0.1	-18.6	29.0
GN underreporting = 1.0	-2.2		-9.9		3.4		0.0		1.0		1.0		3.1	
GN underreporting	-1.2	1.8	-18.7	29.8	1.2	-1.7	0.0	0.0	0.1	-0.2	0.1	-0.2	1.4	-2.1

Table 5.–Percent difference from baseline values for trap-net mortality (TN F), gill-net mortality (GN F), population biomass, spawning stock biomass per recruit (SSBR) for unfished population, SSBR at reference mortality schedule, SSBR ratio, projected total allowable catch (TAC) or harvest regulating guideline (HRG) from the lake whitefish stock assessment models (WFH-01, WFH-02, WFH-04, and WFH-05) for the 1836 treaty-ceded waters of Lake Huron in 2001, when natural mortality parameter bounds were widened (+) and narrowed (-), and initial values were increased (+) and decreased (-) from the original values. Fishing mortality values are for fish fully selected to the gear.

	TN F		GN F		Biomass		Unfished SSBR		Ref SSBR		SSBR ratio		TAC/HRG	
Description of change	+	-	+	-	+	-	+	-	+	-	+	-	+	-
WFH-01														
Natural mortality bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Natural mortality initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WFH-02														
Natural mortality bounds	-0.2	-0.2	1.2	1.2	4.6	4.6	0.0	0.0	-0.1	-0.1	-0.1	-0.1	34.7	34.7
Natural mortality initial value	-0.2	-0.2	1.2	1.2	4.6	4.6	0.0	0.0	-0.1	-0.1	-0.1	-0.1	34.7	34.5
WFH-04														
Natural mortality bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Natural mortality initial value	0.0	-0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.1
WFH-05														
Natural mortality bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Natural mortality initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6.–Percent difference from baseline values for trap-net mortality (TN F), gill-net mortality (GN F), population biomass, spawning stock biomass per recruit (SSBR) for unfished population, SSBR at reference mortality schedule, SSBR ratio, projected total allowable catch (TAC) or harvest regulating guideline (HRG) from the lake whitefish stock assessment models (WFH-01, WFH-02, WFH-04, and WFH-05) for the 1836 treaty-ceded waters of Lake Huron in 2001, when catchability parameter bounds were widened (+) and narrowed (-), and initial values were increased (+) and decreased (-) from the original values. Fishing mortality values are for fish fully selected to the gear.

	TN F		GN F		Biomass		Unfished SSBR		Ref SSBR		SSBR ratio		TAC/HRG	
Description of change	+	-	+	-	+	-	+	-	+	-	+	-	+	-
WFH-01														
TN catchability bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TN catchability initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GN catchability bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GN catchability initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WFH-02														
TN catchability bounds	0.0	-0.2	0.0	1.2	0.0	4.6	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	34.7
TN catchability initial value	-0.2	-0.2	1.2	1.2	4.6	4.6	0.0	0.0	-0.1	-0.1	-0.1	-0.1	34.7	34.7
GN catchability bounds	-0.2	-0.2	1.2	1.2	4.6	4.6	0.0	0.0	-0.1	-0.1	-0.1	-0.1	34.7	34.7
GN catchability initial value	-0.2	0.0	1.2	0.0	4.6	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	34.7	0.0
WFH-04														
TN catchability bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TN catchability initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GN catchability bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GN catchability initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WFH-05														
TN catchability bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TN catchability initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GN catchability bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GN catchability initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 7.–Percent difference from baseline values for trap-net mortality (TN F), gill-net mortality (GN F), population biomass, spawning stock biomass per recruit (SSBR) for unfished population, SSBR at reference mortality schedule, SSBR ratio, projected total allowable catch (TAC) or harvest regulating guideline (HRG) from the lake whitefish stock assessment models (WFH-01, WFH-02, WFH-04, and WFH-05) for the 1836 treaty-ceded waters of Lake Huron in 2001, when population abundance parameter bounds were widened (+) and narrowed (-), and initial values were increased (+) and decreased (-) from the original values. Fishing mortality values are for fish fully selected to the gear.

	TN F		GN F		Biomass		Unfished SSBR		Ref SSBR		SSBR ratio		TAC/HRG	
Description of change	+	-	+	-	+	-	+	-	+	-	+	-	+	-
WFH-01														
Population scalar bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Population scalar initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Population deviation bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WFH-02														
Population scalar bounds	-0.2	-0.2	1.2	1.2	4.6	4.6	0.0	0.0	-0.1	-0.1	-0.1	-0.1	34.7	34.7
Population scalar initial value	0.0	-0.2	0.0	1.2	0.0	4.6	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	34.7
Population deviation bounds	0.0	8.0	0.0	31.9	0.0	0.0	0.0	0.0	0.0	2.2	0.0	2.2	0.0	25.2
WFH-04														
Population scalar bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Population scalar initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Population deviation bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WFH-05														
Population scalar bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Population scalar initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Population deviation bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 8.–Percent difference from baseline values for trap-net mortality (TN F), gill-net mortality (GN F), population biomass, spawning stock biomass per recruit (SSBR) for unfished population, SSBR at reference mortality schedule, SSBR ratio, projected total allowable catch (TAC) or harvest regulating guideline (HRG) from the lake whitefish stock assessment models (WFH-01, WFH-02, WFH-04, and WFH-05) for the 1836 treaty-ceded waters of Lake Huron in 2001, when recruitment parameter bounds were widened (+) and narrowed (-), and initial values were increased (+) and decreased (-) from the original values. Fishing mortality values are for fish fully selected to the gear. Some changes resulted in the models failing to converge (fc).

	TN F		GN F		Biomass		Unfished SSBR		Ref SSBR		SSBR ratio		TAC/HRG	
Description of change	+	-	+	-	+	-	+	-	+	-	+	-	+	-
WFH-01														
Recruitment α bounds	0.0	0.9	0.0	0.2	0.0	-3.4	0.0	0.0	0.0	-0.6	0.0	-0.6	0.0	-9.2
Recruitment α initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recruitment β bounds	0.0	3.0	0.0	0.8	0.0	-15.2	0.0	0.0	0.0	-2.4	0.0	-2.4	0.0	-43.4
Recruitment β initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WFH-02														
Recruitment α bounds	-0.4	fc	1.1	fc	5.4	fc	0.0	fc	0.0	fc	0.0	fc	37.2	fc
Recruitment α initial value	-0.2	fc	1.2	fc	4.6	fc	0.0	fc	-0.1	fc	-0.1	fc	34.7	fc
Recruitment β bounds	-0.2	0.0	1.2	0.0	4.6	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	34.7	0.0
Recruitment β initial value	-0.2	-0.2	1.2	1.2	4.6	4.6	0.0	0.0	-0.1	-0.1	-0.1	-0.1	34.7	34.7
WFH-04														
Recruitment α bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recruitment α initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recruitment β bounds	0.0	-0.3	0.0	1.2	0.0	-2.1	0.0	0.0	0.0	2.4	0.0	2.4	0.0	-20.6
Recruitment β initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WFH-05														
Recruitment α bounds	0.0	10.8	0.0	10.5	0.0	-5.4	0.0	0.0	0.0	1.0	0.0	1.0	0.0	-7.1
Recruitment α initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recruitment β bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recruitment β initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 9.–Percent difference from baseline values for trap-net mortality (TN F), gill-net mortality (GN F), population biomass, spawning stock biomass per recruit (SSBR) for unfished population, SSBR at reference mortality schedule, SSBR ratio, projected total allowable catch (TAC) or harvest regulating guideline (HRG) from the lake whitefish stock assessment models (WFH-01, WFH-02, WFH-04, and WFH-05) for the 1836 treaty-ceded waters of Lake Huron in 2001, when gill-net (GN) selectivity parameter bounds were widened (+) and narrowed (-), and initial values were increased (+) and decreased (-) from the original values. Fishing mortality values are for fish fully selected to the gear. Some changes resulted in the models failing to converge (fc). The selectivity function parameters were the first inflection point (*p1*), first slope (*p2*), second inflection point (*p3*), and second slope (*p4*).

	TN F		GN F		Biomass		Unfished SSBR		Ref SSBR		SSBR ratio		TAC/HRG	
Description of change	+	-	+	-	+	-	+	-	+	-	+	-	+	-
WFH-01														
GN sel. *p1* bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GN sel. *p1* initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GN sel. *p2* bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GN sel. *p2* initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GN sel. *p3* bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GN sel. *p3* initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
GN sel. *p4* initial value	fc	0.0	fc	0.0	fc	0.0	fc	0.0	fc	0.0	fc	0.0	fc	0.0
WFH-02														
GN sel. *p1* bounds	-0.2	6.6	1.2	3.0	4.6	-15.4	0.0	0.0	-0.1	-8.3	-0.1	-8.3	34.7	14.7
GN sel. *p1* initial value	-0.2	-0.2	1.2	1.2	4.6	4.6	0.0	0.0	-0.1	-0.1	-0.1	-0.1	34.7	34.7
GN sel. *p2* bounds	0.0	-0.2	0.0	1.2	0.0	4.6	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	34.7
GN sel. *p2* initial value	0.0	-0.2	0.0	1.2	0.0	4.6	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	34.7
GN sel. *p3* bounds	fc	0.0	fc	0.0	fc	0.0	fc	0.0	fc	0.0	fc	0.0	fc	0.0
GN sel. *p3* initial value	-0.2	-0.2	1.2	1.2	4.6	4.6	0.0	0.0	-0.1	-0.1	-0.1	-0.1	34.7	34.6
GN sel. *p4* initial value	0.0	-0.2	0.0	1.2	0.0	4.6	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	34.7
WFH-04														
GN sel. *p1* bounds	0.0	-4.8	0.0	-9.3	0.0	0.7	0.0	0.0	0.0	-7.9	0.0	-7.9	0.0	2.1
GN sel. *p1* initial value	0.0	fc	0.0	fc	0.0	fc	0.0	fc	0.0	fc	0.0	fc	0.0	fc
GN sel. *p2* bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GN sel. *p2* initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GN sel. *p3* bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GN sel. *p3* initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GN sel. *p4* initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 9.–Continued.

	TN F		GN F		Biomass		Unfished SSBR		Ref SSBR		SSBR ratio		TAC/HRG	
Description of change	+	-	+	-	+	-	+	-	+	-	+	-	+	-
WFH-05														
GN sel. *p1* bounds[a]														
GN sel. *p1* initial value	-9.3	-40.5	127.1	-64.6	44.6	30.9	0.0	0.0	14.4	-5.8	14.4	-5.8	41.7	27.8
GN sel. *p2* bounds[a]														
GN sel. *p2* initial value	-1.1	0.2	6.7	-8.1	4.6	-3.7	0.0	0.0	1.3	-1.2	1.3	-1.2	6.2	-5.6
GN sel. *p3* bounds[a]														
GN sel. *p3* initial value	6.0	131.0	7.1	1,277.2	-2.4	-50.9	0.0	0.0	1.1	10.5	1.1	10.5	-3.7	-87.7
GN sel. *p4* initial value	3.9	-4.6	1.4	1.9	-1.6	2.1	0.0	0.0	0.7	-0.9	0.7	-0.9	-2.4	3.1

[a] not estimated as a parameter

Table 10.–Percent difference from baseline values for trap-net mortality (TN F), gill-net mortality (GN F), population biomass, spawning stock biomass per recruit (SSBR) for unfished population, SSBR at reference mortality schedule, SSBR ratio, projected total allowable catch (TAC) or harvest regulating guideline (HRG) from the lake whitefish stock assessment models (WFH-01, WFH-02, WFH-04, and WFH-05) for the 1836 treaty-ceded waters of Lake Huron in 2001, when trap-net (TN) selectivity parameter bounds were widened (+) and narrowed (-), and initial values were increased (+) and decreased (-) from the original values. Fishing mortality values are for fish fully selected to the gear. Some changes resulted in the models failing to converge (fc). The selectivity function parameters were the first inflection point (*p1*), first slope (*p2*), second inflection point (*p3*), and second slope (*p4*).

	TN F		GN F		Biomass		Unfished SSBR		Ref SSBR		SSBR ratio		TAC/HRG	
Description of change	+	-	+	-	+	-	+	-	+	-	+	-	+	-
WFH-01														
TN sel. *p1* bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TN sel.*p1* initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TN sel. *p3* initial value	0.1	-0.4	0.0	-0.2	0.0	0.1	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	0.1
TN sel. *p4* initial value	0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WFH-02														
TN sel. *p1* bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TN sel. *p1* initial value	fc	-0.2	fc	1.2	fc	4.6	fc	0.0	fc	-0.1	fc	-0.1	fc	34.7
TN sel. *p3* initial value	-0.2	-0.3	1.2	1.2	4.6	4.6	0.0	0.0	-0.1	-0.1	-0.1	-0.1	34.7	34.7
TN sel. *p4* initial value	0.0	-0.2	0.0	1.2	0.0	4.6	0.0	0.0	0.0	-0.1	0.0	-0.1	0.0	34.7
WFH-04														
TN sel. *p1* bounds	0.0	-17.0	0.0	-12.5	0.0	9.0	0.0	0.0	0.0	-5.3	0.0	-5.3	0.0	18.1
TN sel. *p1* initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TN sel. *p3* initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TN sel. *p4* initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WFH-05														
TN sel. *p1* bounds	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TN sel. *p1* initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TN sel. *p3* initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TN sel. *p4* initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 11.–Percent difference from baseline values for trap-net mortality (TN F), gill-net mortality (GN F), population biomass, spawning stock biomass per recruit (SSBR) for unfished population, SSBR at reference mortality schedule, SSBR ratio, projected total allowable catch (TAC) or harvest regulating guideline (HRG) from the lake whitefish stock assessment models (WFH-01, WFH-02, WFH-04, and WFH-05) for the 1836 treaty-ceded waters of Lake Huron in 2001, when likelihood emphasis factors were increased (+) and decreased (-) from the original values. Fishing mortality values are for fish fully selected to the gear. Some changes resulted in the models failing to converge (fc).

	TN F		GN F		Biomass		Unfished SSBR		Ref SSBR		SSBR ratio		TAC/HRG	
Description of likelihood change	+	-	+	-	+	-	+	-	+	-	+	-	+	-
WFH-01														
Natural mortality	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TN catch	fc	0.2	fc	1.8	fc	-4.2	fc	0.0	fc	-0.4	fc	-0.4	fc	-6.3
TN effort	-7.9	13.6	-3.8	6.1	10.4	-11.7	0.0	0.0	1.0	-1.1	0.9	-1.1	17.5	-17.3
TN age composition	fc	0.4	fc	10.2	fc	1.6	fc	0.0	fc	0.4	fc	0.4	fc	14.3
GN catch	0.2	-0.4	0.0	0.2	-0.2	0.5	0.0	0.0	0.3	-0.4	0.3	-0.4	0.3	-0.5
GN effort	2.1	-2.7	5.8	-8.0	-1.0	1.7	0.0	0.0	1.8	-2.9	1.8	-2.9	-1.3	3.4
GN age composition	10.1	-5.5	6.6	-4.0	-12.6	9.0	0.0	0.0	-5.0	8.0	-5.0	8.0	-16.5	11.6
WFH-02														
Natural mortality	-0.2	-0.2	1.2	1.2	4.6	4.6	0.0	0.0	-0.1	-0.1	-0.1	-0.1	34.7	34.6
TN catch	-0.7	0.3	-0.1	3.4	6.4	1.3	0.0	0.0	0.0	-0.3	0.0	-0.3	37.2	30.3
TN effort	-3.0	3.0	-0.9	3.5	11.1	-2.3	0.0	0.0	1.1	-1.7	1.1	-1.7	45.9	23.1
TN age composition	-4.4	3.9	-8.1	17.2	6.1	0.0	0.0	0.0	-1.1	-0.1	-1.1	-0.1	37.1	27.9
GN catch	0.2	7.3	-0.8	34.2	-0.5	1.0	0.0	0.0	-0.2	2.5	-0.2	2.5	-0.8	25.8
GN effort	-0.5	0.6	2.7	-0.6	4.0	4.9	0.0	0.0	-0.1	-0.3	-0.1	-0.3	33.7	36.2
GN age composition	19.4	-6.5	58.3	-9.9	-16.4	15.4	0.0	0.0	0.4	0.3	0.4	0.3	-8.7	62.0
WFH-04														
Natural mortality	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TN catch	fc	-2.2	fc	2.3	fc	-2.4	fc	0.0	fc	0.6	fc	0.6	fc	-3.7
TN effort	-8.6	11.6	-2.9	4.4	2.3	-1.9	0.0	0.0	-2.0	3.4	-2.0	3.4	13.9	-9.8
TN age composition	-5.3	fc	-3.5	fc	5.2	fc	0.0	fc	5.1	fc	5.1	fc	-0.3	fc
GN catch	-0.9	1.1	-0.7	0.9	0.3	-0.1	0.0	0.0	-0.6	0.9	-0.6	0.9	0.7	-0.8
GN effort	-0.9	-1.2	0.1	-2.6	0.4	1.2	0.0	0.0	-0.4	0.2	-0.4	0.2	4.4	-0.6
GN age composition	13.7	fc	12.1	fc	-5.7	fc	0.0	fc	3.3	fc	3.3	fc	-11.3	fc

Table 11.–Continued.

Description of likelihood change	TN F +	TN F -	GN F +	GN F -	Biomass +	Biomass -	Unfished SSBR +	Unfished SSBR -	Ref SSBR +	Ref SSBR -	SSBR ratio +	SSBR ratio -	TAC/HRG +	TAC/HRG -
WFH-05														
Natural mortality	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TN catch	-2.5	4.1	-3.8	6.8	4.4	-7.2	0.0	0.0	-0.7	1.2	-0.7	1.2	5.8	-9.3
TN effort	-9.4	18.9	-2.5	6.3	4.2	-8.4	0.0	0.0	-2.3	3.0	-2.3	3.0	9.9	-16.3
TN age composition	1.0	8.7	-2.1	10.4	19.7	-15.5	0.0	0.0	8.4	-7.3	8.4	-7.2	23.3	-15.4
GN catch	1.6	-2.3	-3.9	7.6	-2.7	4.4	0.0	0.0	-0.9	1.4	-0.9	1.4	-2.4	4.1
GN effort	3.7	-2.6	14.1	-10.5	-7.9	8.0	0.0	0.0	-3.0	3.0	-3.0	3.0	-7.6	7.7
GN age composition	19.0	-12.5	12.2	-8.8	-8.9	7.3	0.0	0.0	3.2	-2.6	3.2	-2.6	-15.6	13.1

Table 12.–Percent difference from baseline values for trap-net mortality (TN F), gill-net mortality (GN F), population biomass, spawning stock biomass per recruit (SSBR) for unfished population, SSBR at reference mortality schedule, SSBR ratio, projected total allowable catch (TAC) or harvest regulating guideline (HRG) from the lake whitefish stock assessment models (WFH-01, WFH-02, WFH-04, and WFH-05) for the 1836 treaty-ceded waters of Lake Huron in 2001, when model structure was modified. Fishing mortality values are for fish fully selected to the gear. Some changes resulted in the models failing to converge (fc).

Description of change	TN F	GN F	Biomass	Unfished SSBR	Ref SSBR	SSBR ratio	TAC/HRG
WFH-01							
Natural mortality constant at initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fecundity linear function of age	0.0	0.0	0.3	0.0	0.1	0.1	0.8
Recruitment unconstrained	fc	fc	fc	fc	fc	fc	fc
Recruitment Beverton-Holt model	0.4	0.5	0.3	0.0	0.3	0.3	1.7
Fit fishery biomass	fc	fc	fc	fc	fc	fc	fc
Gamma likelihood component	0.1	-0.1	0.3	0.0	0.1	0.1	0.5
Dirichlet likelihood component	-2.9	20.1	-8.4	0.0	17.6	17.6	-16.9
WFH-02							
Natural mortality constant at initial value	-0.2	1.2	4.6	0.0	-0.1	-0.1	34.7
Fecundity linear function of age	-0.5	1.0	5.9	0.0	0.0	0.0	38.8
Recruitment unconstrained	-0.1	-0.1	0.2	0.0	0.0	0.0	0.6
Recruitment Beverton-Holt model	-1.0	0.7	8.0	0.0	0.4	0.4	42.9
Fit fishery biomass	8.4	39.6	6.9	0.0	5.4	5.4	3.7
Gamma likelihood component	fc	fc	fc	fc	fc	fc	fc
Dirichlet likelihood component	6.2	1.5	-0.4	0.0	-3.8	-3.8	25.9
WFH-04							
Natural mortality constant at initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fecundity linear function of age	fc	fc	fc	fc	fc	fc	fc
Recruitment unconstrained	fc	fc	fc	fc	fc	fc	fc
Recruitment Beverton-Holt model	-10.0	-3.5	18.6	0.0	6.9	6.9	54.3
Fit fishery biomass	-6.2	-4.9	15.7	0.0	5.0	5.0	14.6
Gamma likelihood component	0.1	-0.3	0.3	0.0	0.0	0.0	0.5
Dirichlet likelihood component	-0.1	-4.7	2.2	0.0	0.0	0.0	0.5

Table 12.–Continued.

Description of change	TN F	GN F	Biomass	Unfished SSBR	Ref SSBR	SSBR ratio	TAC/HRG
WFH-05							
Natural mortality constant at initial value	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fecundity linear function of age	1.0	0.4	-3.2	0.0	-0.6	-0.6	-5.1
Recruitment unconstrained	-3.8	-1.5	23.0	0.0	4.5	4.5	39.8
Recruitment Beverton-Holt model	-5.5	-5.7	16.7	0.0	4.3	4.3	20.8
Fit fishery biomass	-2.9	-10.2	19.3	0.0	8.2	8.2	12.8
Gamma likelihood component	-0.1	0.7	0.4	0.0	0.1	0.1	0.4
Dirichlet likelihood component	9.9	5.1	-11.6	0.0	-1.4	-1.4	-18.0

Table 13.–Predicted values for trap-net mortality (TN F), gill-net mortality (GN F), population biomass (lbs), spawning stock biomass per recruit (SSBR) for unfished population, SSBR at reference mortality schedule, SSBR ratio, projected total allowable catch (TAC) or harvest regulating guideline (HRG; lbs), and the negative log-likelihood values from the lake whitefish stock assessment models for the 1836 treaty-ceded waters of Lake Huron in 2001, when changes improved model fit. Fishing mortality values are for fish fully selected to the gear. The selectivity function parameter *p4* was the second slope. Selectivity was abbreviated sel., and decrease was abbreviated dec.

Description of change	TN F	GN F	Biomass	Unfished SSBR	Ref SSBR	SSBR ratio	TAC/HRG	Likelihood
WFH-01								
Recruitment β bounds dec.	0.07	0.38	2,032,260	0.38	0.12	0.30	212,169	6,405.53
WFH-04								
Recruitment β bounds dec.	0.23	0.36	2,292,740	0.42	0.13	0.31	264,482	5,688.16
WFH-05								
GN sel. *p4* initial value dec.	0.34	0.003	4,876,080	0.34	0.17	0.49	902,314	2,981.44

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Appendix A.–A list of the changes made to the stock assessment models (WFH-01, WFH-02, WFH-04, and WFH-05) for lake whitefish in the 1836 treaty waters of Lake Huron. The selectivity function parameters for the trap-net (TN) and gill-net (GN) fisheries were the first inflection point (*p1*), first slope (*p2*), second inflection point (*p3*), and second slope (*p4*).

0: baseline model
1: TN weight-at-age values increased by 20%
2: TN weight-at-age values decreased by 20%
3: GN weight-at-age values increased by 20%
4: GN weight-at-age values decreased by 20%
5: Maturity schedule shifted up by 1 yr
6: Maturity schedule shifted down by 1 yr
7: GN net height adjustment factor set to 1.0
8: GN net height adjustment factor modifier set to 0.8
9: GN net height adjustment factor modifier set to 1.2
10: TN underreporting values set to 1.0
11: TN underreporting values increased by 0.2
12: TN underreporting values decreased by 0.2
13: GN underreporting values set to 1.0
14: GN underreporting values increased by 0.2
15: GN underreporting values decreased by 0.2
16: Proportion of females in population set to 0.5
17: Proportion of females in population increased by 0.2
18: Proportion of females in population decreased by 0.2
19: Time of spawning increased by 0.2
20: Time of spawning decreased by 0.2
21: Natural mortality parameter bounds widened by 20%
22: Natural mortality parameter bounds narrowed by 20%
23: TN catchability parameter bounds widened by 20%
24: TN catchability parameter bounds narrowed by 20%
25: GN catchability parameter bounds widened by 20%
26: GN catchability parameter bounds narrowed by 20%
27: GN selectivity *p1* parameter bounds widened by 20%
28: GN selectivity *p1* parameter bounds narrowed by 20%
29: GN selectivity *p2* parameter bounds widened by 20%
30: GN selectivity *p2* parameter bounds narrowed by 20%
31: GN selectivity *p3* parameter bounds widened by 20%
32: GN selectivity *p3* parameter bounds narrowed by 20%
33: GN selectivity *p4* parameter bounds widened by 20%
34: GN selectivity *p4* parameter bounds narrowed by 20%
35: TN selectivity *p1* parameter bounds widened by 20%
36: TN selectivity *p1* parameter bounds narrowed by 20%
37: TN selectivity *p2* parameter bounds widened by 20%

38: TN selectivity *p2* parameter bounds narrowed by 20%
39: TN selectivity *p3* parameter bounds widened by 20%
40: TN selectivity *p3* parameter bounds narrowed by 20%
41: TN selectivity *p4* parameter bounds widened by 20%
42: TN selectivity *p4* parameter bounds narrowed by 20%
43: GN selectivity time-varying parameter 1 bounds widened by 20%
44: GN selectivity time-varying parameter 1 bounds narrowed by 20%
45: GN selectivity time-varying parameter 2 bounds widened by 20%
46: GN selectivity time-varying parameter 2 bounds narrowed by 20%
47: TN selectivity time-varying parameter 1 bounds widened by 20%
48: TN selectivity time-varying parameter 1 bounds narrowed by 20%
49: TN selectivity time-varying parameter 2 bounds widened by 20%
50: TN selectivity time-varying parameter 2 bounds narrowed by 20%
51: Population scaling parameter bounds widened by 20%
52: Population scaling parameter bounds narrowed by 20%
53: Relative population deviations parameter bounds widened by 20%
54: Relative population deviations parameter bounds narrowed by 20%
55: Recruitment productivity parameter bounds widened by 20%
56: Recruitment productivity parameter bounds narrowed by 20%
57: Recruitment density dependent parameter bounds widened by 20%
58: Recruitment density dependent parameter bounds narrowed by 20%
59: TN effort deviations parameter bounds widened by 20%
60: TN effort deviations parameter bounds narrowed by 20%
61: GN effort deviations parameter bounds widened by 20%
62: GN effort deviations parameter bounds narrowed by 20%
63: TN catchability parameter starting value increased by 20%
64: TN catchability parameter starting value decreased by 20%
65: GN catchability parameter starting value increased by 20%
66: GN catchability parameter starting value decreased by 20%
67: Population scaling parameter starting value increased by 20%
68: Population scaling parameter starting value decreased by 20%
69: GN selectivity *p1* parameter starting value increased by 20%
70: GN selectivity *p1* parameter starting value decreased by 20%
71: GN selectivity *p2* parameter starting value increased by 20%
72: GN selectivity *p2* parameter starting value decreased by 20%
73: GN selectivity *p3* parameter starting value increased by 20%
74: GN selectivity *p3* parameter starting value decreased by 20%
75: GN selectivity *p4* parameter starting value increased by 20%
76: GN selectivity *p4* parameter starting value decreased by 20%
77: TN selectivity *p1* parameter starting value increased by 20%

Appendix A.–Continued.

78: TN selectivity *p1* parameter starting value decreased by 20%
79: TN selectivity *p2* parameter starting value increased by 20%
80: TN selectivity *p2* parameter starting value decreased by 20%
81: TN selectivity *p3* parameter starting value increased by 20%
82: TN selectivity *p3* parameter starting value decreased by 20%
83: TN selectivity *p4* parameter starting value increased by 20%
84: TN selectivity *p4* parameter starting value decreased by 20%
85: Recruitment productivity parameter starting value increased by 20%
86: Recruitment productivity parameter starting value decreased by 20%
87: Recruitment density dependent parameter starting value increased by 20%
88: Recruitment density dependent parameter starting value decreased by 20%
89: Natural mortality likelihood weighting factor doubled
90: Natural mortality likelihood weighting factor halved
91: TN catch likelihood weighting factor doubled
92: TN catch likelihood weighting factor halved
93: TN effort likelihood weighting factor doubled
94: TN effort likelihood weighting factor halved
95: TN age composition likelihood weighting factor doubled
96: TN age composition likelihood weighting factor halved
97: GN catch likelihood weighting factor doubled
98: GN catch likelihood weighting factor halved
99: GN effort likelihood weighting factor doubled
100: GN effort likelihood weighting factor halved
101: GN age composition likelihood weighting factor doubled
102: GN age composition likelihood weighting factor halved
103: Natural mortality held constant
104: Natural mortality parameter starting value increased by 20%
105: Natural mortality parameter starting value decreased by 20%
106: Fecundity as linear function of weight
107: Recruitment estimated as free parameters
108: Recruitment estimated with Beverton-Holt function
109: TN and GN catches in biomass used
110: Gamma likelihood used for TN and GN catches
111: Dirichlet likelihood used for TN and GN age compositions
The following changes were made to the WFH-05 model only:
112: GN selectivity time-varying parameter 1 starting value increased by 20%
113: GN selectivity time-varying parameter 1 starting value decreased by 20%
114: GN selectivity time-varying parameter 2 starting value increased by 20%
115: GN selectivity time-varying parameter 2 starting value decreased by 20%